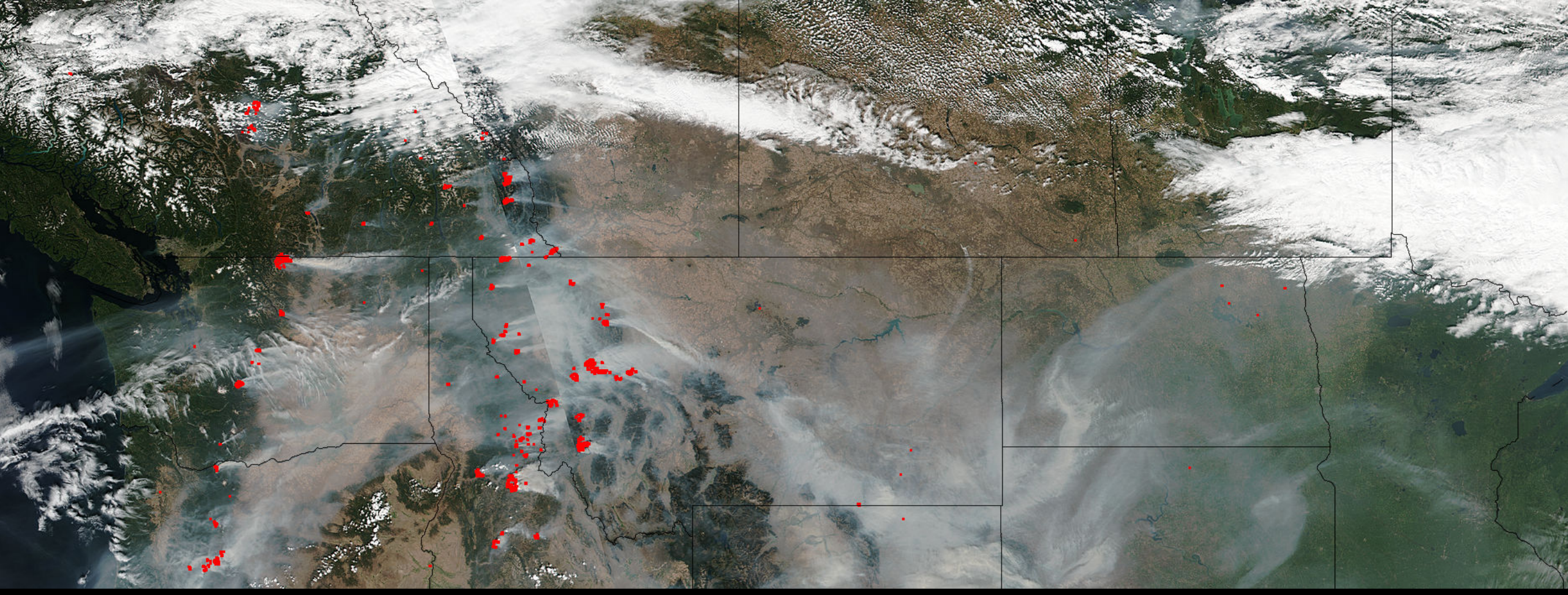


Air Quality Forecasting and the MERRA-2 Reanalysis

Melanie Follette-Cook and Pawan Gupta

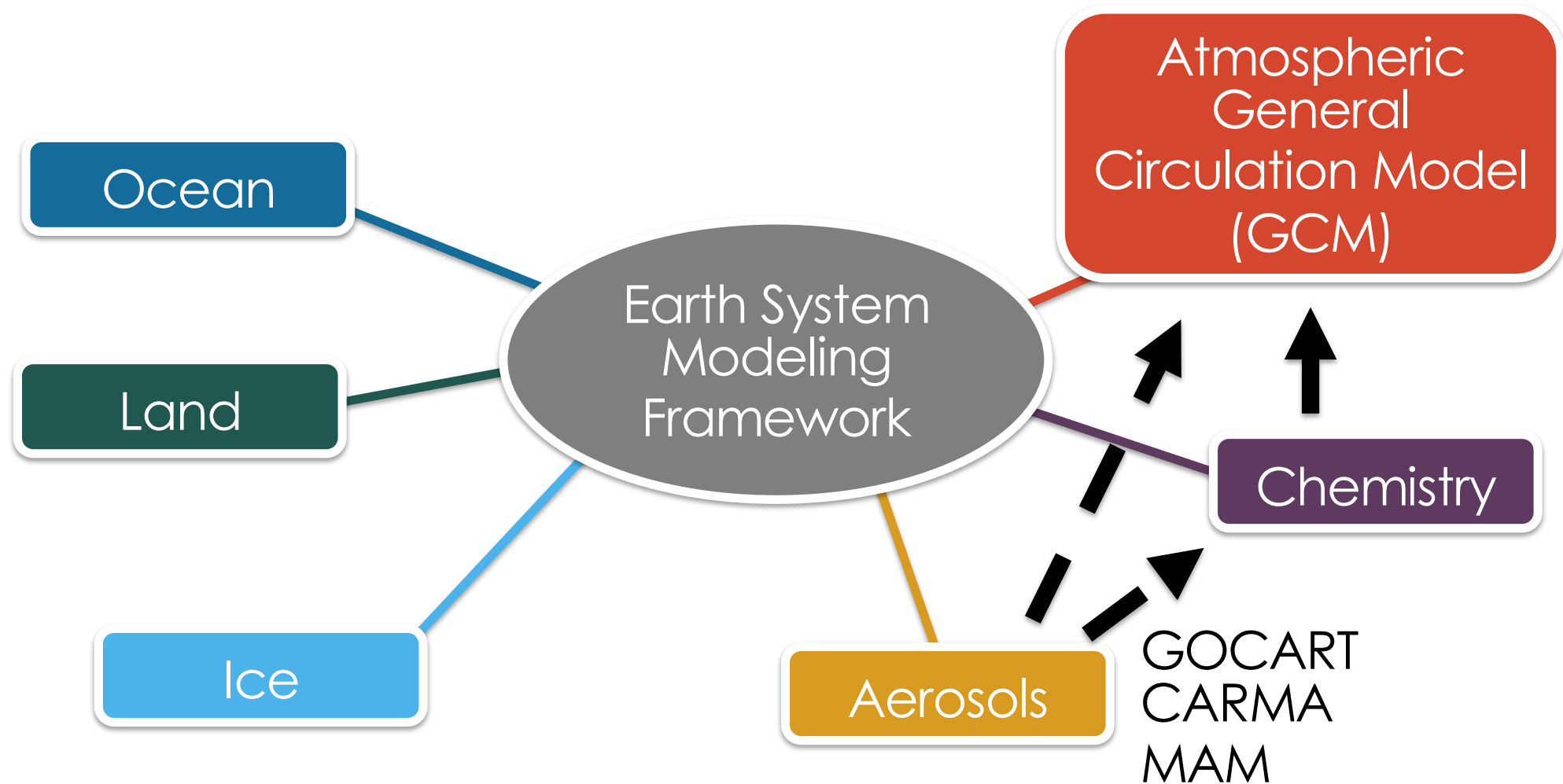
Satellite Remote Sensing of Dust, Fires, Smoke, and Air Quality, July 10-12, 2018





MERRA-2 Reanalysis

NASA GEOS Earth System Model



Why data assimilation?

- Models are useful but have difficulty specifying emissions, resolving microphysical processes, and transport, leading to large uncertainties
- While there are a large number of aerosol sensors, there are still blind spots:
 - Measurements are usually vertically integrated
 - Diurnal cycle is not represented by polar orbiters
- Data assimilation can act as an integrator of model and observational information and a conveyor of past observations



What is reanalysis, and why do we do it?

What

- A consistent reprocessing of Earth system observations using a modern, unchanging data assimilation system
- Relies on models to interpret, relate, and combine different observations from multiple sources
- A successful reanalysis **requires** a good forecast model combined with bias-corrected and quality controlled observations

Why

- Produces multi-decadal, gridded datasets that estimate a large variety of Earth system variables, including ones that are not directly observed
- Has become fundamental to research and education in the Earth sciences



MERRA-2 Reanalysis

<https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/>

- Long-term, model-based analyses of multiple datasets using a fixed assimilation system
 - GEOS (Goddard Earth Observing System Model)
- The **M**odern-**E**ra **R**etrospective analysis for **R**esearch and **A**pplications version 2 (MERRA-2) provides data beginning in 1980 and runs a few weeks behind real-time
- MERRA-2 includes meteorology, stratospheric ozone, and aerosols at a spatial resolution of a $0.5^\circ \times 0.66^\circ$ grid



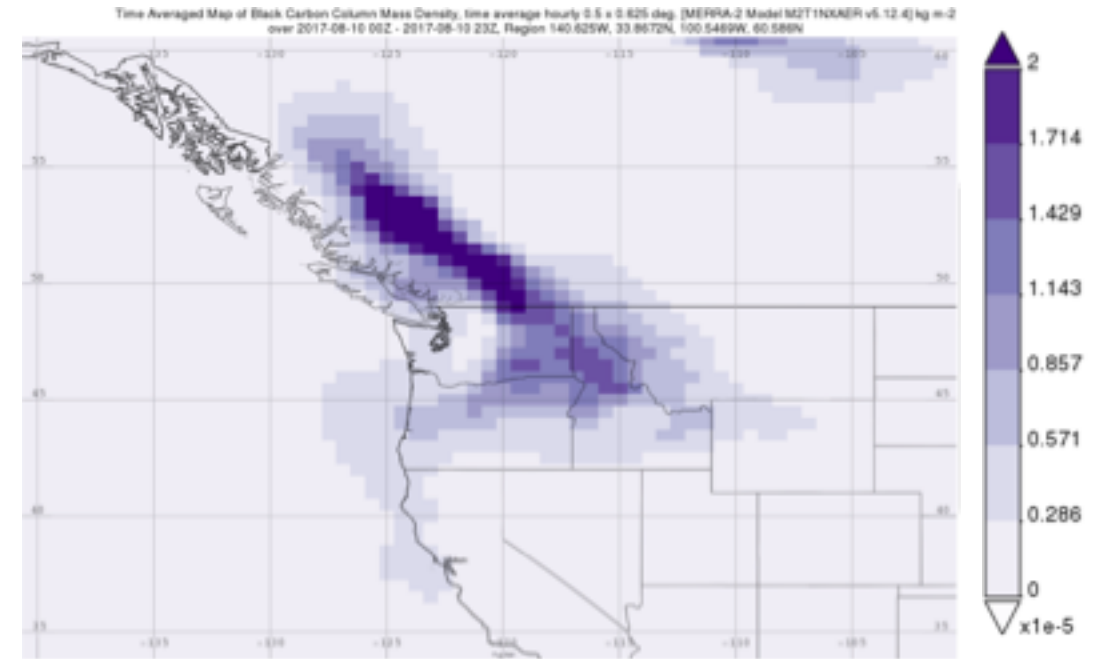
Source: <https://gmao.gsfc.nasa.gov/reanalysis/>



MERRA-2 Reanalysis Example – August 10, 2017



MERRA-2 – Black Carbon



MERRA-2 Webpage Tour

<https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/>

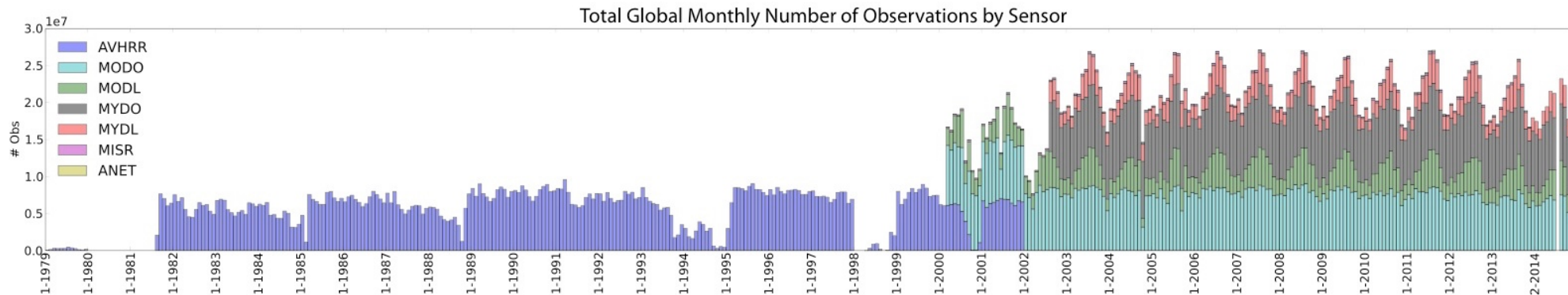
The screenshot shows the NASA Goddard Space Flight Center website for the Global Modeling and Assimilation Office (GMAO). The header includes the NASA logo, the text "National Aeronautics and Space Administration Goddard Space Flight Center", and "Earth Sciences Division | Sciences and Exploration". A search bar with a "GO" button is also present. The main navigation bar features several tabs: "GMAO MISSION", "WEATHER ANALYSIS & PREDICTION", "SEASONAL-DECADAL ANALYSIS & PREDICTION", "REANALYSIS", "GLOBAL MESOSCALE MODELING", and "OBSERVING SYSTEM SCIENCE". The "REANALYSIS" tab is selected, leading to the "MERRA-2 Project" page. On the left, a sidebar menu lists links: "MERRA-2 Project", "Data Access", "Documentation", "Highlights", "Images", "Videos", "FAQ", "Publications", "Mailing List", "User Metrics", and "Diagnostic Feedback". The main content area is titled "Modern-Era Retrospective analysis for Research and Applications, Version 2" and includes a "Project Overview" section. The overview text states: "The Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) provides data beginning in 1980. It was introduced to replace the original MERRA dataset because of the advances made in the assimilation system that enable assimilation of modern hyperspectral radiance and microwave observations, along with GPS-Radio Occultation datasets. It also uses NASA ozone observations after 2005. Additional advances in both the GEOS-5 model and the GSI assimilation system are included in MERRA-2. Spatial resolution remains about the same (about 50 km in the latitudinal direction) as in MERRA." A second paragraph follows: "Along with the enhancements in the meteorological assimilation, MERRA-2 takes some significant steps towards GMAO's target of an Earth System reanalysis. MERRA-2 is the first long-term global reanalysis to assimilate space-based observations of aerosols and represent their interactions with other physical processes in the climate system. MERRA-2 includes a representation of ice sheets over (say) Greenland and Antarctica." Below the text is a large graphic featuring a globe with several smaller inset maps showing different atmospheric variables, and the text "GMAO" and "MERRA-2 Modern-Era Retrospective Analysis for Research and Applications, Version 2".



Aerosol Observing System

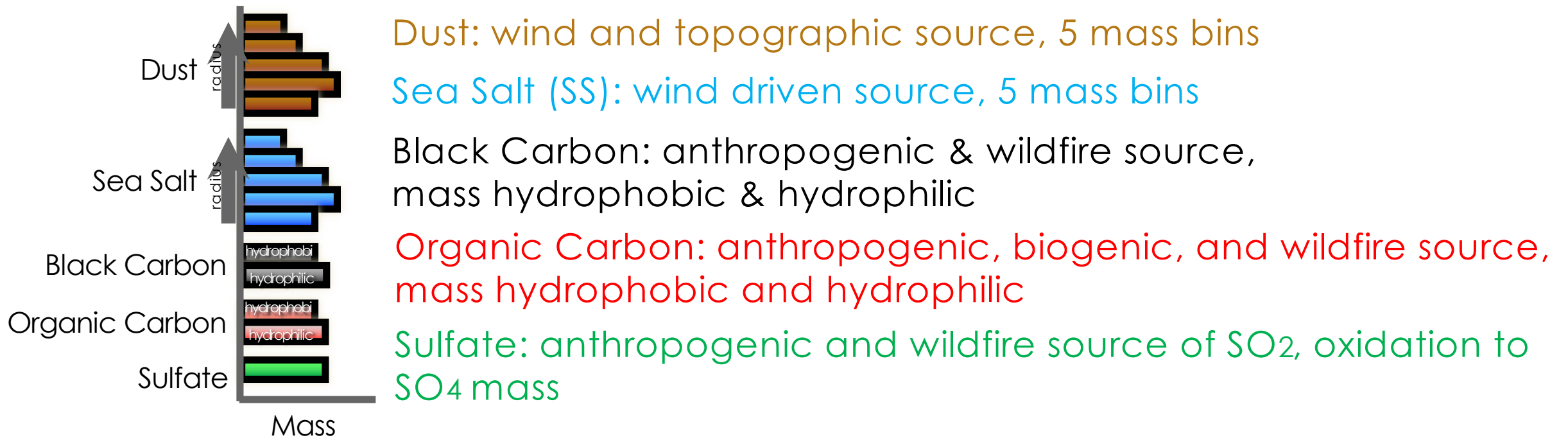
Sensor	Period	Remarks
AVHRR*	1979 – 2002	PATMOS-x; NNR; Ocean Only
AERONET	1999 – 2015	Ground-Based Stations
MODIS Terra*	2000 - present	C5; NNR; Separate Land and Ocean
MODIS Aqua*	2002 – present	C5; NNR; Separate Land and Ocean
MISR	2000 – 2014	Bright Surfaces (albedo > 0.15)

Total global monthly number of AOD observations, sensors marked with * multiplied by 10^7



GOCART in GEOS-5

- Based on the Goddard Chemistry, Aerosol, Radiation and Transport Model (Chin et al. 2002)
- Sources and sinks for 5 non-interactive species



MERRA-2 Emissions

<https://gmao.gsfc.nasa.gov/pubs/docs/Randles887.pdf>

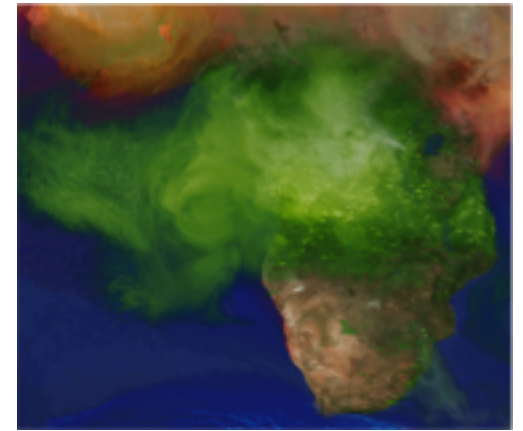


Table 2.1: Aerosol and precursor emissions in MERRA-2

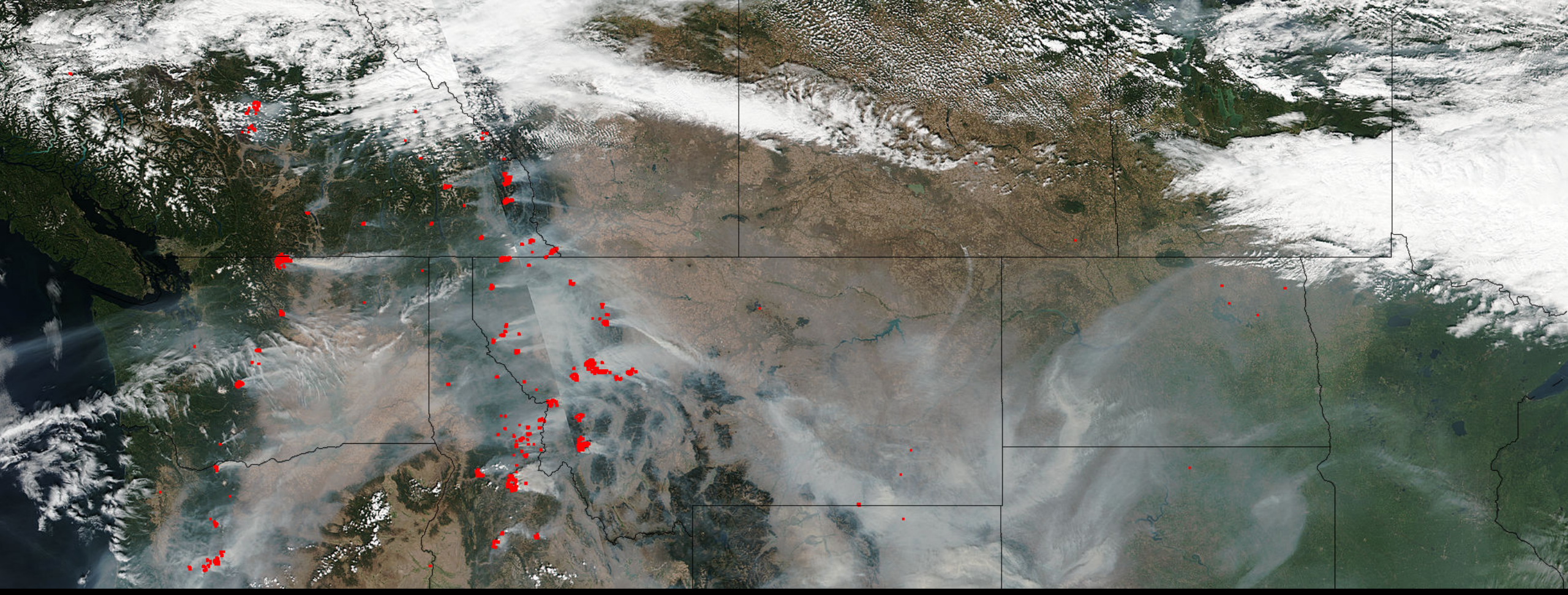
Aerosol Type	Source	Temporal Resolution	Spatial Resolution ^{a,b}
Dust	Wind-driven emissions w/ Ginoux et al. (2001) static topographic depression map	Model	$0.3125^\circ \times 0.25^\circ$ ^c
Sea Salt	Wind-driven emissions	Model	Model
Volcanic (SO ₂)	AeroCom Phase II (HCA0 v2; Diehl et al., 2012)	Daily degassing (1980 – onwards) and daily eruptive (1980 – 2010)	Point-sources
Biogenic terpene	Guenther et al. (1995)	Monthly-mean climatology	$2^\circ \times 2.5^\circ$
Di-Methyl Sulfide (DMS)	Lana et al. (2011)	Monthly-mean climatology	$1^\circ \times 1^\circ$
Biomass Burning (SO ₂ , SO ₄ , POM, and BC)	scaled RETROv2 (Duncan et al., 2003) scaled GFEDv3.1 (Randerson et al., 2006) QFED 2.4-r6 (Darmenov and da Silva, 2015)	Monthly-varying (1980 – 1996) Monthly-varying (1997 – 2010) Daily-varying (2010 – onwards)	$0.3125^\circ \times 0.25^\circ$ $0.3125^\circ \times 0.25^\circ$ $0.3125^\circ \times 0.25^\circ$
Anthropogenic SO ₂	EDGARv4.2 (Energy + Non-Energy) (European Commission, 2011)	Annually-varying (1980 – 2008)	$0.1^\circ \times 0.1^\circ$
Anthropogenic SO ₄ , POM, and BC	AeroCom Phase II (HCA0 v1; Diehl et al., 2012)	Annually-varying (1980 – 2006)	$1^\circ \times 1^\circ$
International Ships SO ₂	EDGARv4.1 (European Commission, 2010)	Annually-varying (1980 – 2005)	$1^\circ \times 1^\circ$
International Ships SO ₄ , POM, and BC	AeroCom Phase II (HCA0 v1; Diehl et al., 2012)	Annually-varying (1980 – 2007)	$1^\circ \times 1^\circ$
Aircraft SO ₂	AeroCom Phase II (HCA0 v1; Diehl et al., 2012)	Monthly-varying (1980 – 2006)	$1^\circ \times 1.25^\circ \times 72$ -levels

^a Model = MERRA-2 time-step of 30 minutes with spatial resolution of 0.5° latitude \times 0.625° longitude.

^b latitude \times longitude

^c Resolution is for source map ([Ginoux et al., 2001](#)); wind-driven emissions at model time-step and grid.





Evaluation & Inter-Comparisons

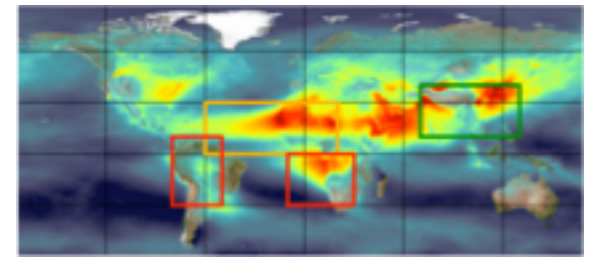
MERRA-2 Aerosol Evaluation Highlights

Using Independent Observations

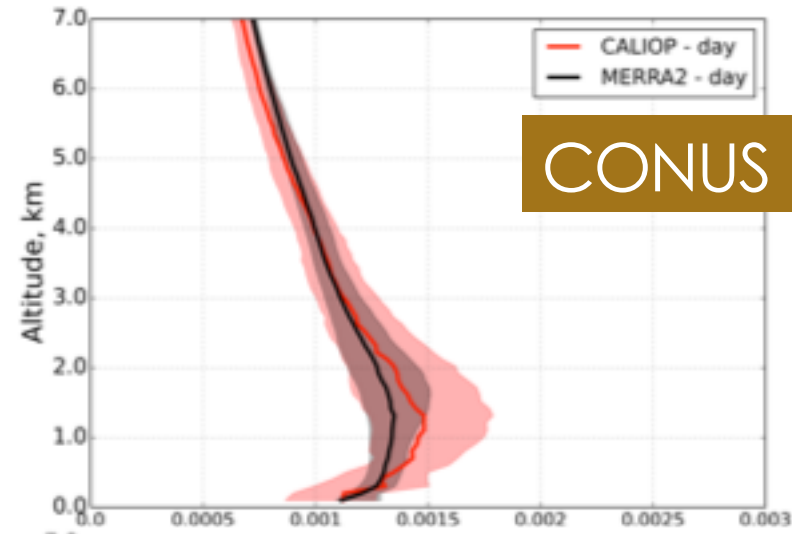


Vertical Structure

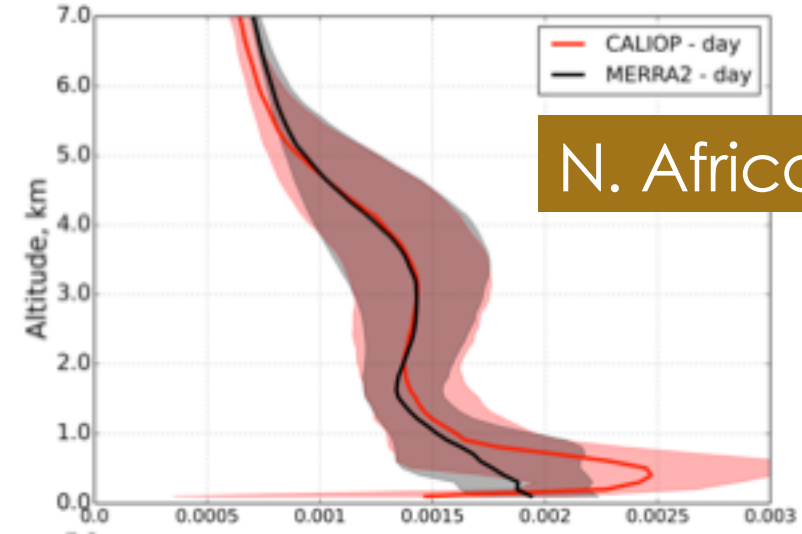
Comparison to CALIOP



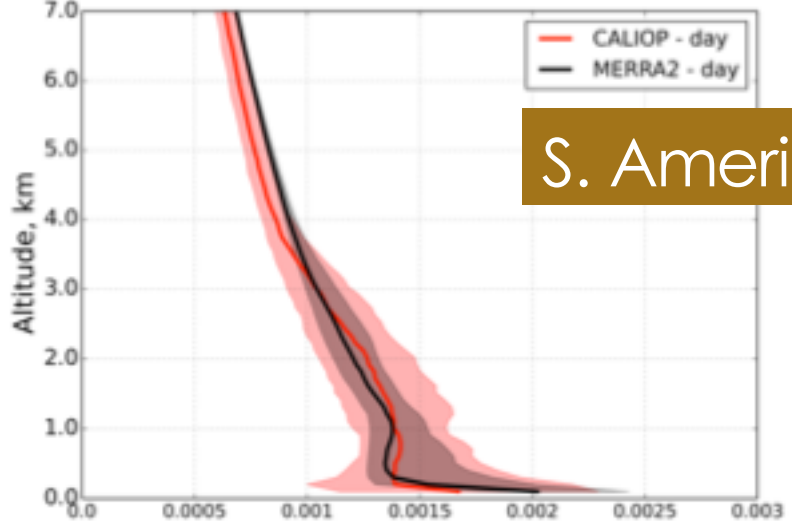
Attenuated Backscatter $\text{km}^{-1} \text{sr}^{-1}$



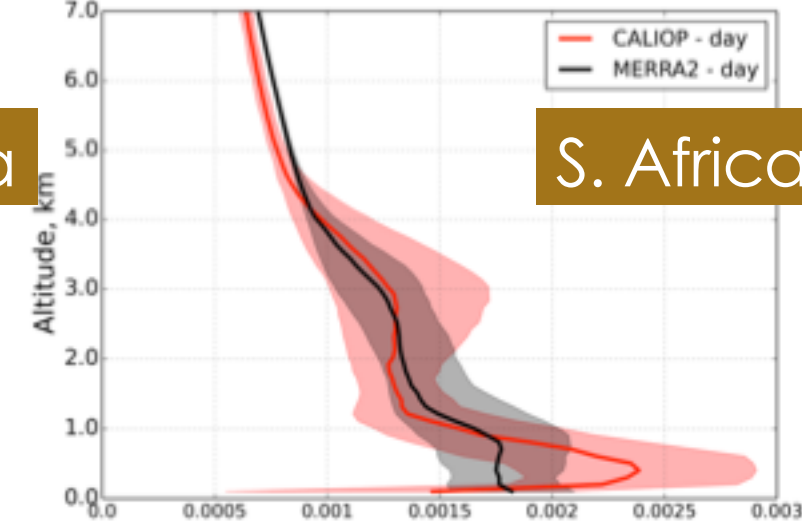
CONUS



N. Africa



S. America

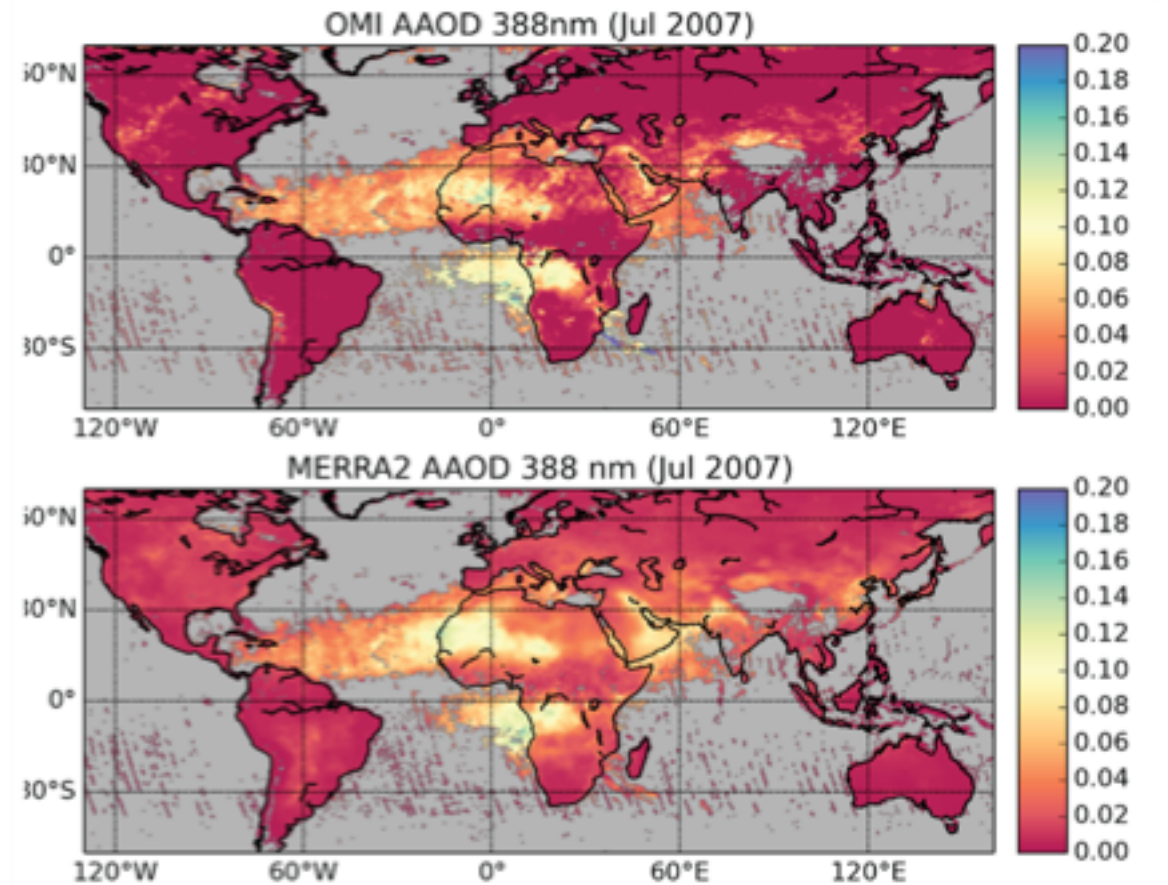


S. Africa

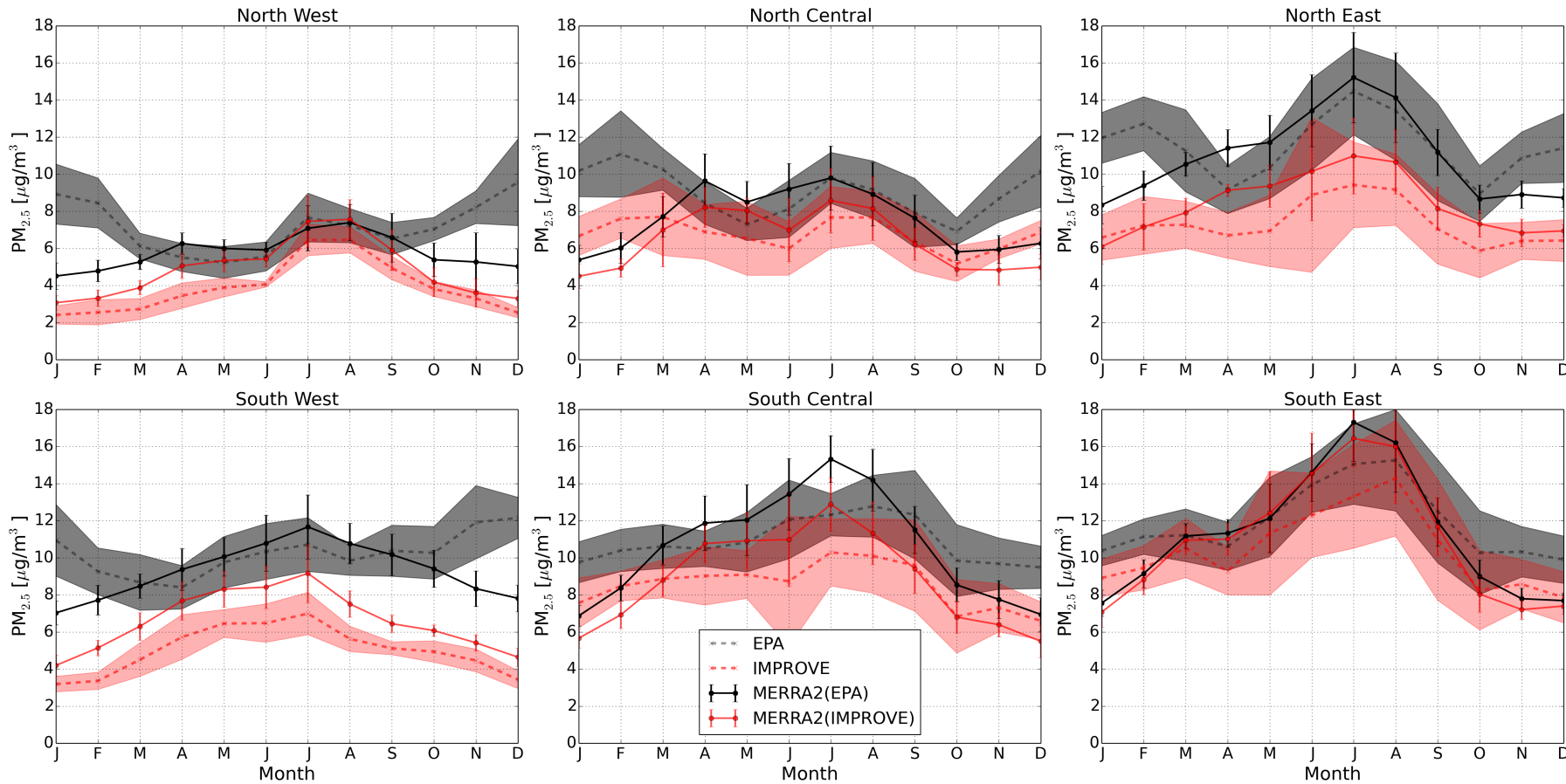


Aerosol Absorption

- Comparison of MERRA-2 Absorption Optical Depth (AAOD) with OMI retrievals
- Good agreement for African dust and smoke
- North American biomass burning underestimated according to OMI



PM_{2.5} (Total) Regional Climatology

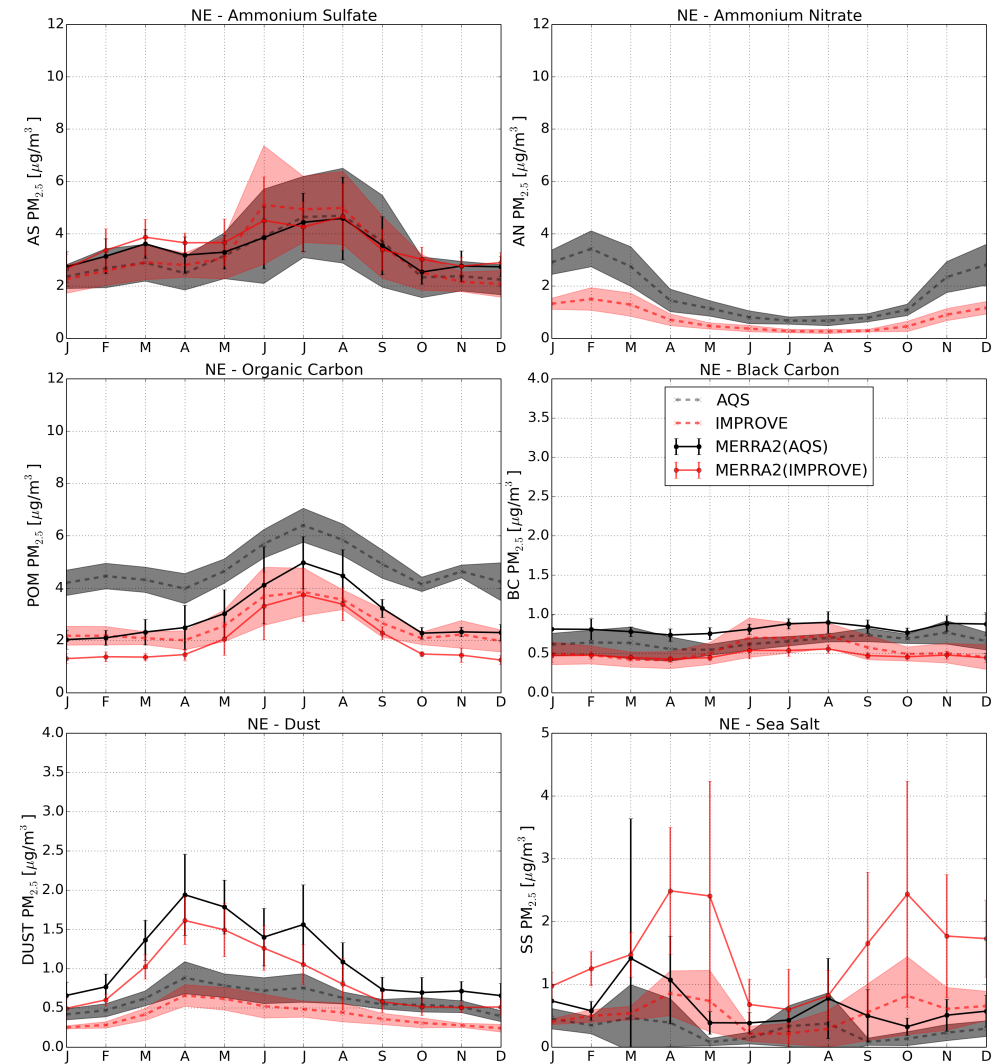


Comparison with in-situ measurements



PM_{2.5} by Species in the Northeast

- Relatively good agreement for **sulfates**
- MERRA-2 lacks **nitrates** altogether
- Underestimation of **carbonaceous** near-urban areas
- Too much **dust**
- Too much **sea salt** at coastal stations



MERRA-2 Status

- MERRA-2 has officially been released. Data access through the GES DISC:
 - <http://disc.sci.gsfc.nasa.gov/daac-bin/FTPSubset2.pl>
 - <https://disc.gsfc.nasa.gov/datasets?keywords=merra-2&page=1>
- The MERRA-2 file specification document is available at:
 - <http://gmao.gsfc.nasa.gov/pubs/> under the tab *Office Notes (GMAO Office Note No. 9)*
- NASA tech memos documenting the MERRA-2 meteorological and aerosol validation are available at:
 - <https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/docs/>
- MERRA-2 Aerosol publications:
 - Randles et al., Journal of Climate, 2017, DOI: 10.1175/JCLI-D-16-0609.1
 - Buchard et al., Journal of Climate, 2017, DOI: 10.1175/JCLI-D-16-0613.1



Exercise: Create a visualization of MERRA-2 output using Giovanni

- Select your event from the list below

- Fires in Canada and Smoke Transport Over the U.S., June 09, 2015

http://earthobservatory.nasa.gov/IOTD/view.php?id=86011&eocon=image&eoci=related_image

- Buffalo Fires, Wyoming, August 13, 2016

<http://go.nasa.gov/2cWvi9z>

- Saharan Dust Crosses the Atlantic, June 1, 2010

<http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=44169>

- Fires in Indonesia, September 24, 2015:

<http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=86681>

- Fires in Australia, February 10, 2014:

<http://earthobservatory.nasa.gov/IOTD/view.php?id=83117>

- Haze Over Eastern Asia, February 25, 2014:

<http://earthobservatory.nasa.gov/IOTD/view.php?id=83213>



Exercise: Create a visualization of MERRA-2 output using Giovanni

<https://giovanni.gsfc.nasa.gov/giovanni/>

- On the left side, under Platform/Instrument, select MERRA-2 model

The screenshot shows the Giovanni web interface. On the left, the 'Platform / Instrument' menu is expanded, and 'MERRA-2 Model (234)' is selected, indicated by a red circle. The main area displays a list of data products, including 'Total eastward wind analysis tendency', 'Total northward wind analysis tendency', and various 'Dust Dry Deposition Bin' and 'Dust Wet Deposition Bin' products. The interface includes buttons for 'Help', 'Reset', 'Feedback', and 'Plot Data' at the bottom right.

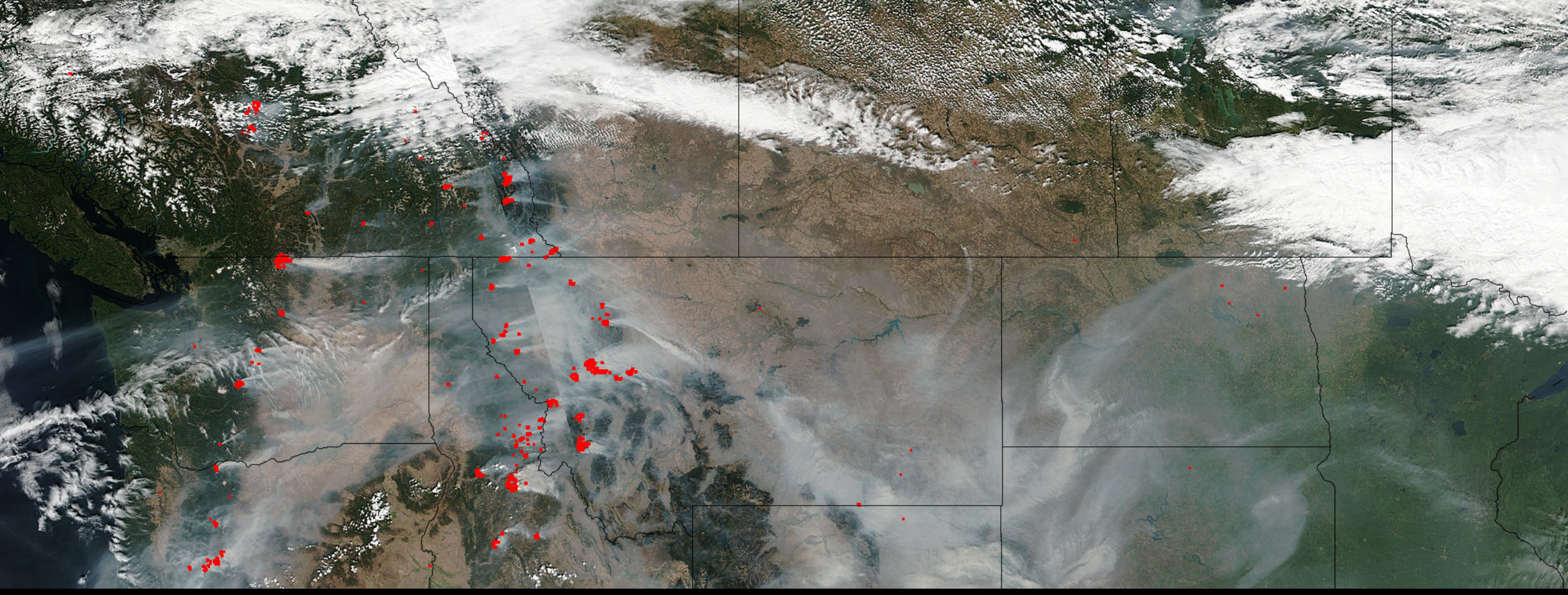
Platform / Instrument	Product Name	Units	Model	Temporal Resolution	Lat Range	Lon Range	Start Date	End Date	Pressure
MERRA-2 Model	Total eastward wind analysis tendency (M2TMNPUdT v5.12.4)	m s-2	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	1000 hPa	
MERRA-2 Model	Total northward wind analysis tendency (M2TMNPUdT v5.12.4)	m s-2	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	1000 hPa	
MERRA-2 Model	Dust Dry Deposition Bin-1 (M2TMNXADG v5.12.4)	kg m-2 s-1	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	-	
MERRA-2 Model	Dust Dry Deposition Bin-2 (M2TMNXADG v5.12.4)	kg m-2 s-1	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	-	
MERRA-2 Model	Dust Dry Deposition Bin-3 (M2TMNXADG v5.12.4)	kg m-2 s-1	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	-	
MERRA-2 Model	Dust Dry Deposition Bin-4 (M2TMNXADG v5.12.4)	kg m-2 s-1	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	-	
MERRA-2 Model	Dust Dry Deposition Bin-5 (M2TMNXADG v5.12.4)	kg m-2 s-1	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	-	
MERRA-2 Model	Dust Wet Deposition Bin-1 (M2TMNXADG v5.12.4)	kg m-2 s-1	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	-	
MERRA-2 Model	Dust Wet Deposition Bin-2 (M2TMNXADG v5.12.4)	kg m-2 s-1	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	-	
MERRA-2 Model	Dust Wet Deposition Bin-3 (M2TMNXADG v5.12.4)	kg m-2 s-1	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	-	
MERRA-2 Model	Dust Wet Deposition Bin-4 (M2TMNXADG v5.12.4)	kg m-2 s-1	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	-	
MERRA-2 Model	Dust Wet Deposition Bin-5 (M2TMNXADG v5.12.4)	kg m-2 s-1	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	-	
MERRA-2 Model	Black Carbon Column Mass Density (M2TMNXAER v5.12.4)	kg m-2	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	-	
MERRA-2 Model	Black Carbon Extinction AOT 550 nm (M2TMNXAER v5.12.4)	-	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	-	
MERRA-2 Model	Black Carbon Scattering AOT 550 nm (M2TMNXAER v5.12.4)	-	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	-	
MERRA-2 Model	Black Carbon Surface Mass Concentration (M2TMNXAER v5.12.4)	kg m-3	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	-	
MERRA-2 Model	Dust Column Mass Density (M2TMNXAER v5.12.4)	kg m-2	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	-	
MERRA-2 Model	Dust Column Mass Density - PM 2.5 (M2TMNXAER v5.12.4)	kg m-2	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	-	
MERRA-2 Model	Dust Extinction AOT 550 nm - PM 2.5 (M2TMNXAER v5.12.4)	-	MERRA-2 Model	Monthly	0.5 x 0.625 °	1980-01-01	2018-05-31	-	



Exercise: Create a visualization of MERRA-2 output using Giovanni

- Select the appropriate geophysical parameter relevant to the air quality event (i.e. dust AOD for dust transport, BC for fires, etc.)
- Create any one of the following visualizations
 - Multi day animation map showing the event
 - Time series over a certain region showing the impact of event
 - Time averaged maps





NASA GEOS Forecasts

NASA Forecasts: <https://fluid.nccs.nasa.gov/weather/>

- NASA's global weather and atmospheric composition forecasts
 - Currently, the forecast system does include aerosols and CO, but not other trace gases like ozone and NO₂

The screenshot shows the NASA GMAO website interface. At the top, there is a NASA logo on the left and the text "Global Modeling and Assimilation Office GMAO" on the right. Below this is a navigation bar with links for "Weather", "Seasonal", "Reanalysis", and "Mission Support". The main content area is titled "Weather Analyses and Forecasts" and is divided into four panels:

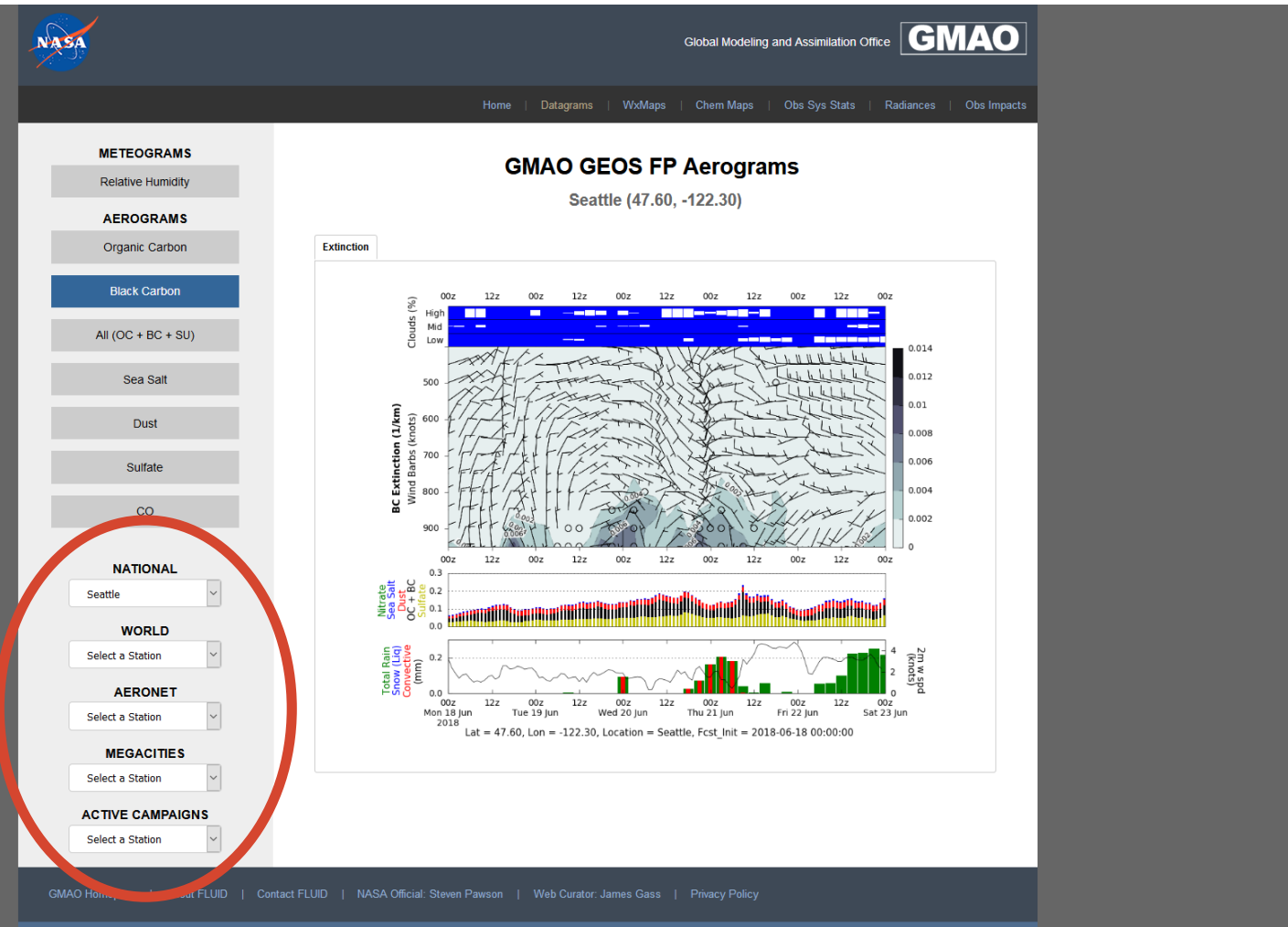
- Datagrams:** A vertical plot showing relative humidity (%) on the y-axis (0 to 100) and time on the x-axis (from 00z to 00z). It includes a color-coded bar at the top and a secondary x-axis for "3-hr Accum Precip [mm], SLP [mb] and 1000-500mb Thickness [dam]".
- WxMaps:** A map of the United States showing weather patterns, including precipitation and cloud cover. A color scale at the bottom indicates "3-hr Accum Precip [mm], SLP [mb] and 1000-500mb Thickness [dam]" with values from 0.5 to 200.
- Chem Maps:** A map showing "Dust Aerosol Optical Thickness" with a color scale from 0.05 to 1.81.
- Observing System Statistics:** A plot titled "12z 2018-06-17 METOP-A AMSUA: TB Obs [K]" showing temperature observations from the METOP-A satellite.

On the left side of the interface, there is a "Navigation" menu with links to Datagrams, WxMaps, Chem Maps, Observing System Stats, Radiances Monitoring, Observation Impacts, and WMS Viewer: GEOS Aerosols. Below that is a "Data Access" menu with links for HTTPS, OPeNDAP, and FTP (No Password), each with sub-links for Assimilation and Forecast.



NASA Atmospheric Composition Forecasts: Datagrams

View plots for select cities, AERONET locations, and NASA field campaigns

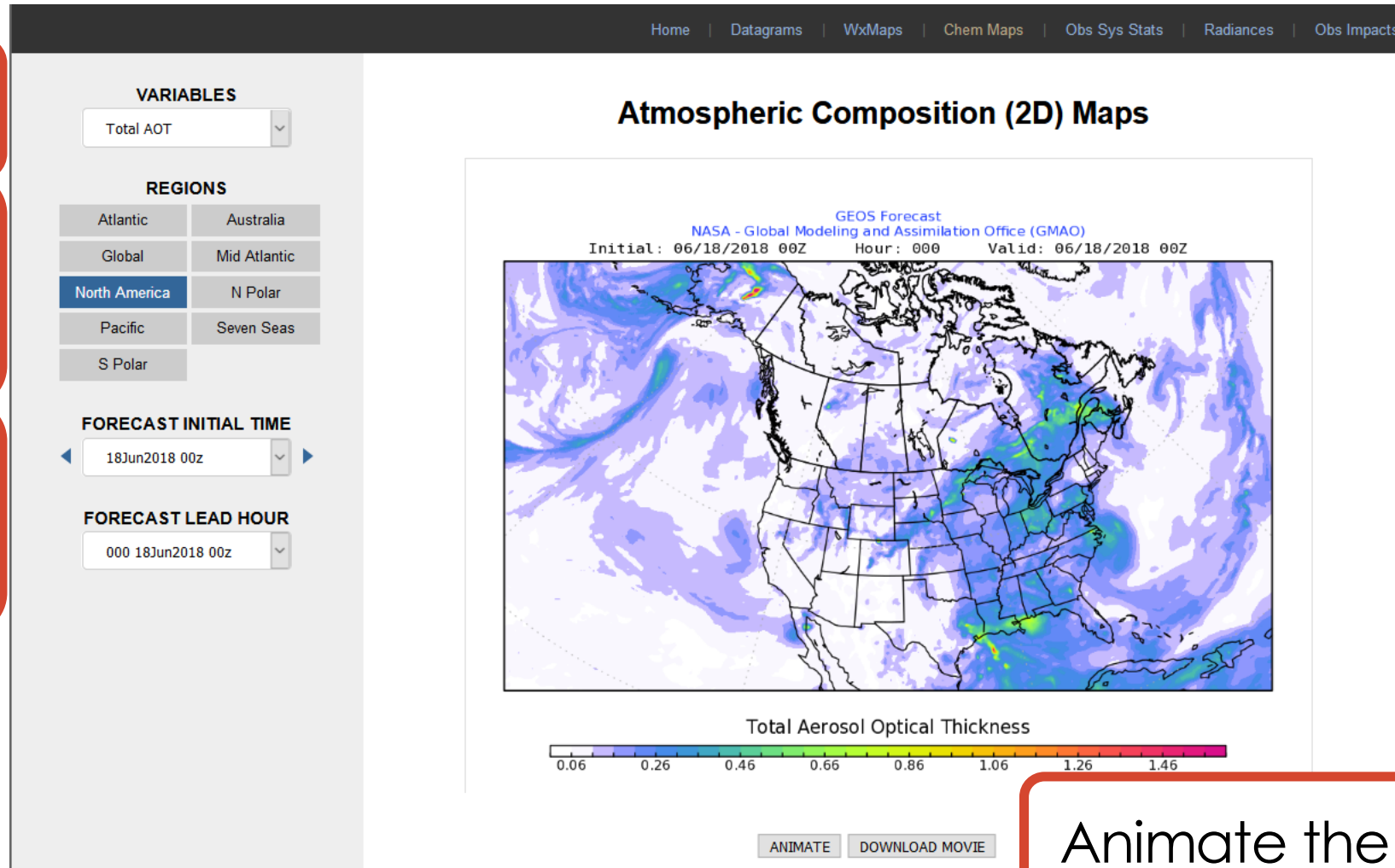


NASA Atmospheric Composition Forecasts: Chem Maps

Select a variable

Select a map region

Select a forecast



Animate the map



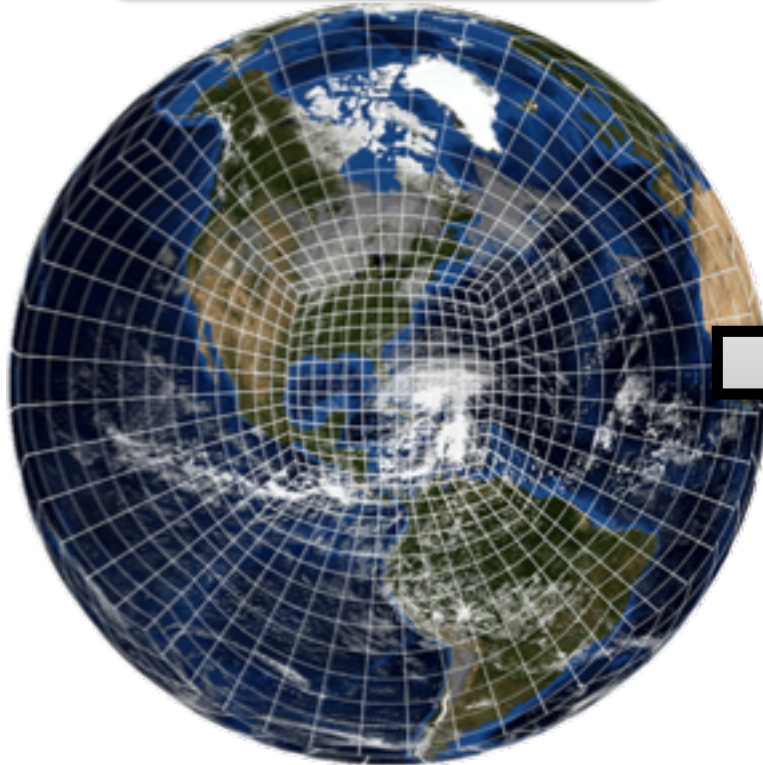
NASA Atmospheric Composition Forecasts: Exercise

- Compare the forecast for the chemical composition of aerosols in Spokane to that in Washington, DC

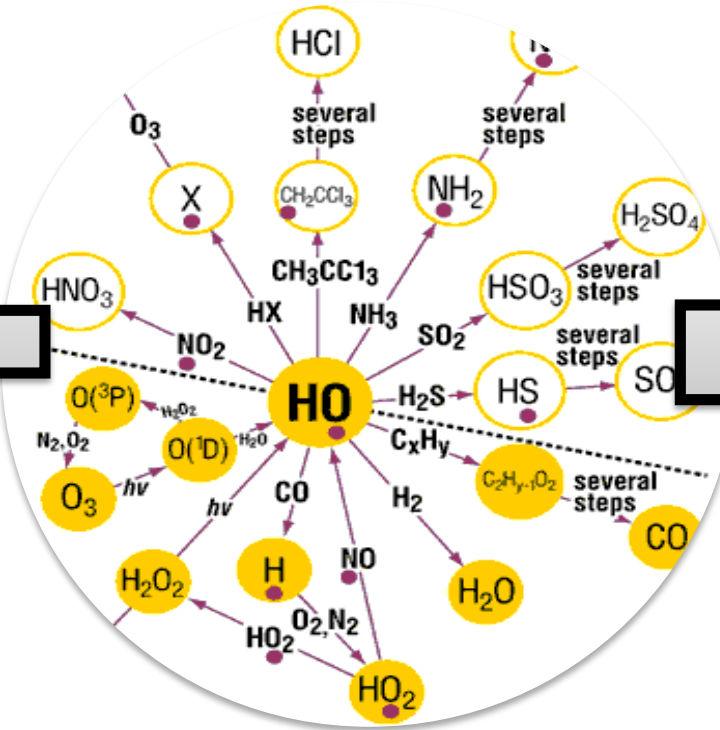


NASA's Upcoming Composition Forecasts (GEOS-CF)

GEOS-FP



GEOS-Chem



GEOS-CF

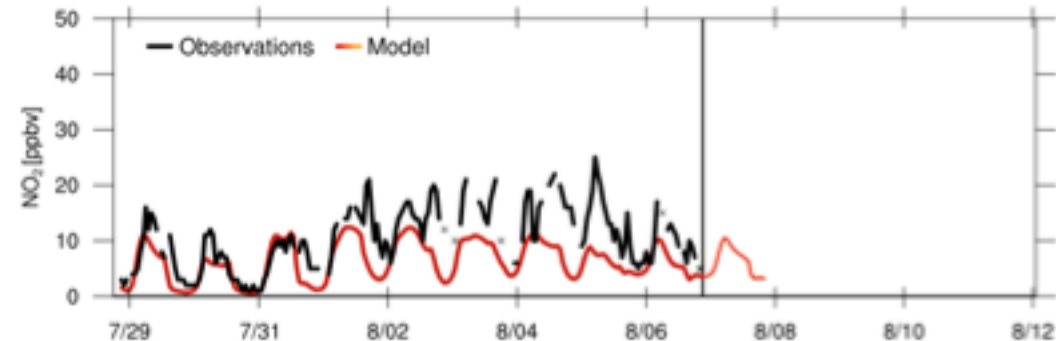
- 1-day analysis
- 5-day forecast
- O₃, NO_x, VOCs, PM ...
- 0.25° resolution



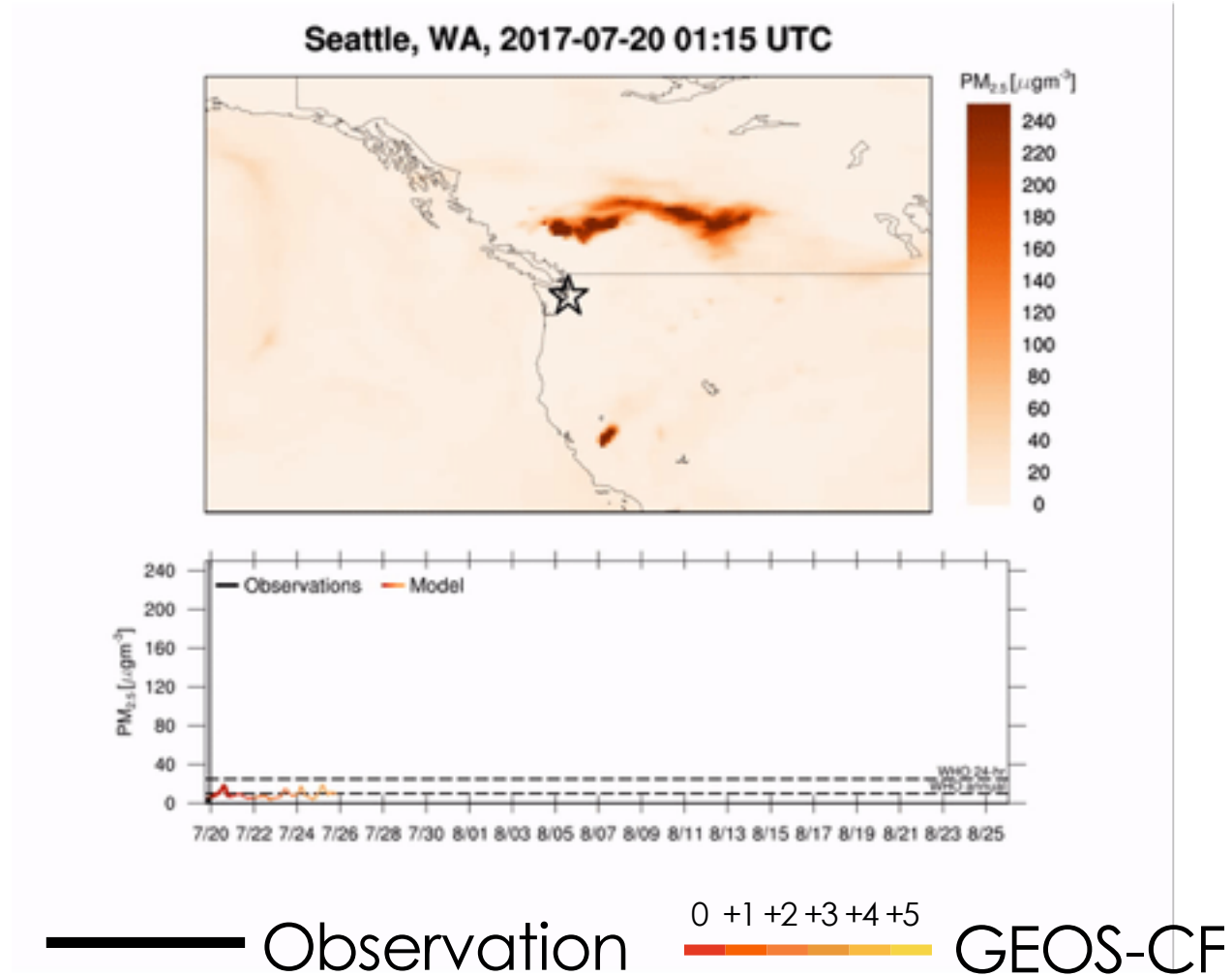
NASA's Upcoming Composition Forecasts

- NASA's global weather and atmospheric composition forecasts
 - Currently, the forecast system does include aerosols and CO, but not other trace gases like ozone and NO₂
 - At some point in 2018, surface particulate matter, ozone, NO₂, and other trace gases will be added to the system

Seattle, WA, 2017-08-06 23:00 UTC



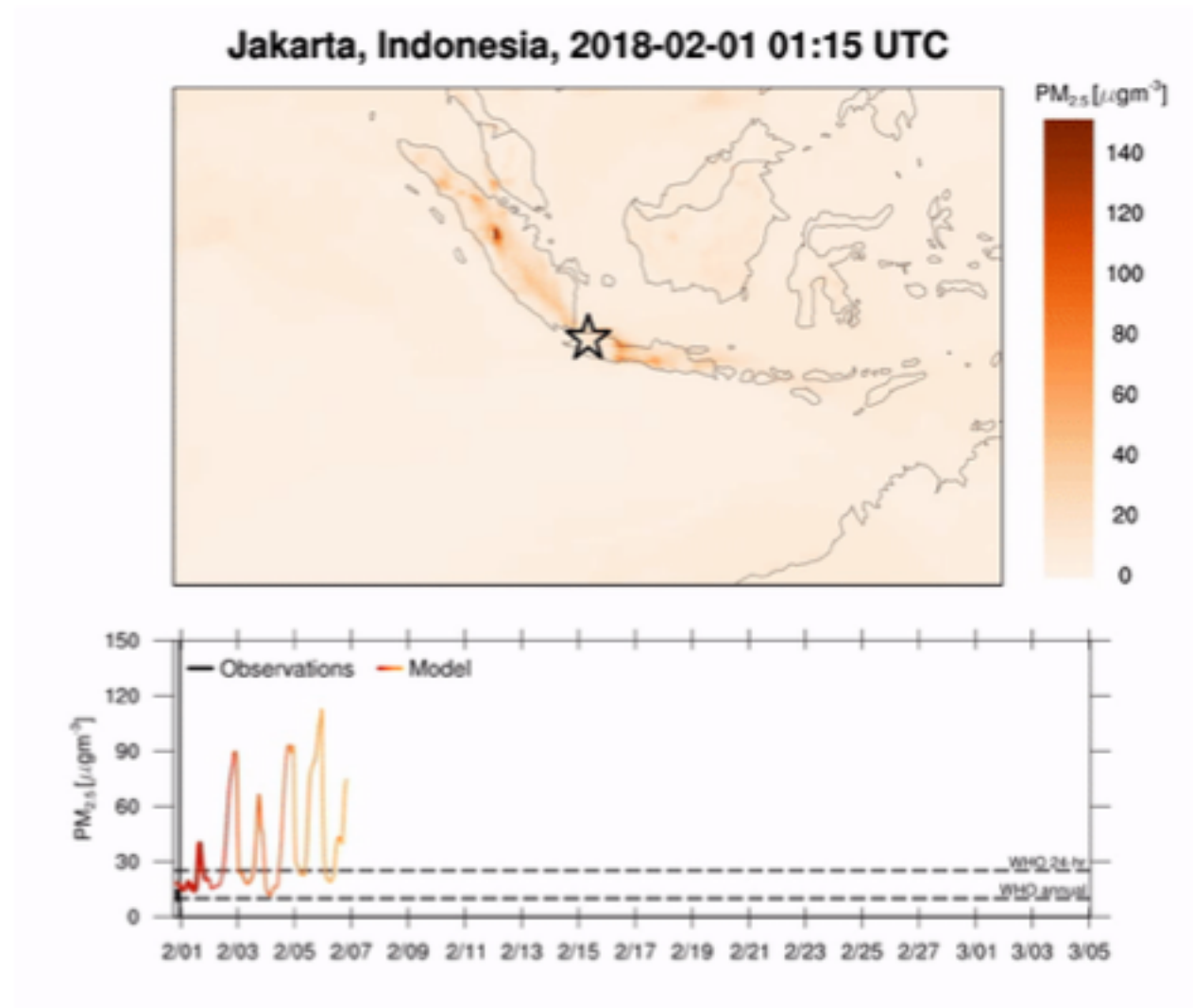
NASA's Upcoming **Air Quality** Forecasts



Christoph Keller, NASA GMAO



NASA's Upcoming **Air Quality** Forecasts

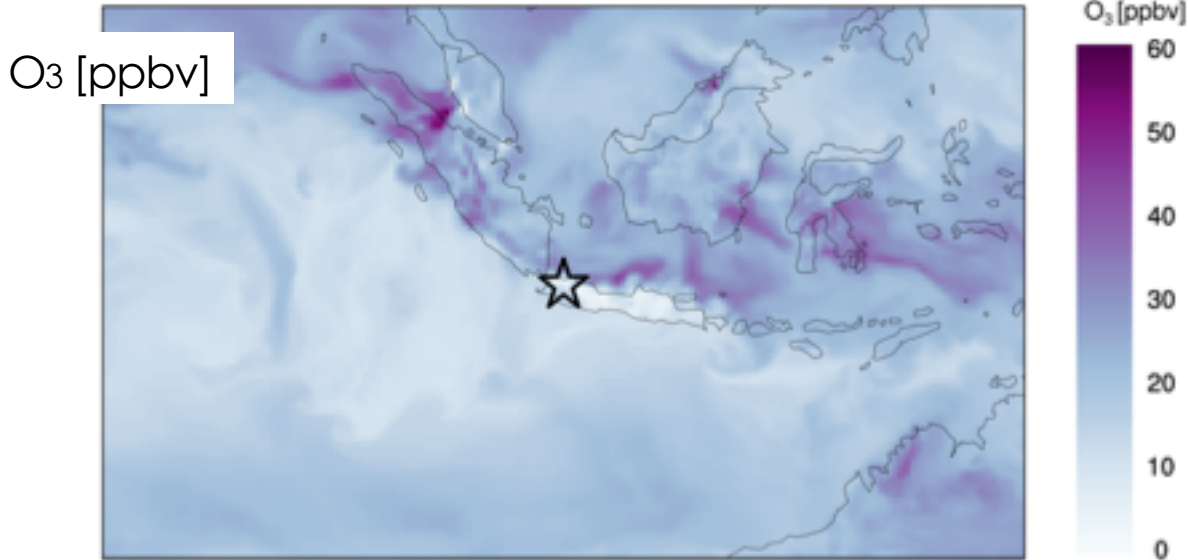


Christoph Keller, NASA GMAO



NASA's Upcoming **Air Quality** Forecasts

Jakarta, Indonesia, 2018-02-27 23:45 UTC



Jakarta, Indonesia, 2018-02-27 23:45 UTC

